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General Features of Quantum Creep in High-T_c Superconductors

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Measurements of the relaxation rate $Q(T)$ of superconducting currents have been performed on a carefully selected set of *dirty* and *clean* high-T_c superconductors for temperatures T down to 100 mK and magnetic fields up to 7 T. The extrapolated relaxation rates $Q(0)$ for the dirty compounds indicate that the viscosity experienced by a tunneling vortex segment is grossly underestimated by the standard Bardeen-Stephen theory. For the clean compounds a universal value $Q(0) \cong 0.022$ is found at 1 T, implying that the number of superconducting charge carriers involved in the tunneling of a vortex segment is $\cong$14. [S0031-9007(98)06075-X]

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Soon after the report of large relaxation of the superconducting current at low temperatures in high-T_c superconductors (HTS's) it was proposed that quantum tunneling of almost macroscopic vortex segments could be responsible for this dissipation. In *dirty* superconductors tunneling of vortices is a dissipative process [1]. From the work of Blatter, Geshkenbein, and Vinokur [2] one obtains that in this case the normalized relaxation rate $Q_{\mathrm{dirty}}(0)$ of supercurrents in the quantum regime at $T = 0$ is given by

$$Q_{\mathrm{dirty}}(0) \cong \frac{e^2}{\hbar} \frac{\rho_n(0)}{L_c(0)} \tag{1}$$

in case of single vortex tunneling. Here $\rho_n(0)$ is the normal state resistivity and $L_c(0)$ the length of the tunneling vortex segment, at $T = 0$ K and with the magnetic field applied along the c axis. For the case of weak collective pinning $L_c(0) \cong (\xi_{ab}/\gamma)(j_0/j_c)^{1/2}$, where ξ_{ab} is the Ginzburg-Landau coherence length in the ab plane, $\gamma \equiv \sqrt{(m_z/m)}$ the anisotropy, j_0 the depairing current density, and j_c the critical current density, all at $T = 0$ K. For strongly layered HTS's Blatter *et al.* [3] argue that Eq. (1) is still valid provided that $L_c(0)$ is replaced by the distance d between the CuO_2 layers, since here the moving objects are pancake vortices with thickness d.

To show that Eq. (1) predicts the right order of magnitude theorists have usually taken values for the archetypal HTS $YBa_2Cu_3O_7$ and with $\xi_{ab}(0) \approx 1.5$ nm, $\gamma \cong 10$, $j_0/j_c \cong 100$, and $\rho_n(0) \cong 10\ \mu\Omega$ cm they obtain $Q_{\mathrm{dirty}}(0) \cong 0.02$ close to the experimentally observed values. However, this agreement might be fortuitous since it is arbitrarily assumed that $YBa_2Cu_3O_7$ is in the dirty limit and since the value of $\rho_n(0)$ cannot be determined unambiguously for HTS's such as $YBa_2Cu_3O_7$ where the extrapolation of $\rho_n(T)$ from data above T_c ($\cong 90$ K) all the way down to 0 K is not at all reliable. To the best of our knowledge the dependence of $Q_{\mathrm{dirty}}(0)$ on dissipation (i.e., resistivity) has never been tested quantitatively and systematically so far.

In this Letter we present and analyze quantum creep measurements on two sets of samples which are representative for dirty and clean HTS's. We show that in the dirty limit quantum creep is indeed proportional to $\rho_n(0)/L_c(0)$ but that $L_c(0)$ has to be replaced by an effective length L_{eff} which, in contrast to theoretical expectations, turns out to be much larger than d for certain highly anisotropic HTS's. Since Eq. (1) is derived using the standard Bardeen-Stephen theory [4] for the viscosity experienced by a moving vortex segment, our results imply that this theory is not applicable for the case of a tunneling pancake or similarly that dissipation is not restricted to the CuO_2 plane in which a pancake is moving but extends to neighboring layers.

A completely different behavior is found for *clean* superconductors where the quantum relaxation rate $Q_{\mathrm{clean}}(0)$ at, e.g., $B = 1$ T turns out to be essentially independent of the HTS under investigation. This leads to the intriguing conclusion that in all clean HTS's the number of superconducting charge carriers involved in the tunneling of a vortex segment is typically 14.

We now consider quantum creep in the dirty and clean regimes separately.

(i) *Quantum creep in dirty HTS's.*—For a quantitative check of Eq. (1) it is necessary to make a selection of HTS's according to the following criteria. First, the HTS should be in the dirty limit, i.e., $\omega\tau(0) \ll 1$. Here $\hbar\omega(0) \cong \hbar e B_{c2}(0)/m_e$ is the energy separation between the lowest levels of the electrons localized in the vortex core and $\tau(0)$ the elastic scattering time. With

$\tau(0) = m_e/n_e e^2 \rho_n(0)$ this condition reduces to

$$\omega\tau(0) \cong \frac{\hbar}{2e^2}\frac{1}{n_e \rho_n(0)\xi_{ab}^2(0)} \ll 1\,, \qquad (2)$$

where n_e is the density of electrons in the vortex core. This implies that superconductors are in the dirty limit when they have a high $\xi_{ab}(0)$ [or similarly a low upper critical field $B_{c2}(0)$] and a high $\rho_n(0)$. Second, for $\rho_n(0)$ to be determined unambiguously from extrapolation of $\rho_n(T)$ to $T = 0$ K, the selected materials should have a relatively low T_c and a relatively high resistivity. As a set of HTS's satisfying these criteria we chose oxygen depleted $YBa_2Cu_3O_x$ films, $(YBa_2Cu_3O_7)_n/(PrBa_2Cu_3O_7)_8$ multilayers (consisting of n unit cells of $YBa_2Cu_3O_7$ separated by eight unit cells of $PrBa_2Cu_3O_7$), and electron doped $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ single crystals with various oxygen contents. The $\rho_n(T)$ curves for the dirty HTS's considered here are shown in Fig. 1.

The latter samples are most interesting since they have very high resistivities and low critical fields. For two $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ single crystals [with typical size $1 \times 1 \times 0.1$ mm^3 and oxygen doping resulting in $T_c = 23.2$ K, $B_{c2}(0) \approx 10$ T for sample A and $T_c = 12.1$ K, $B_{c2}(0) \approx 6$ T for sample B; see Ref. [5] for details of the fabrication] the relaxation rate Q has been determined down to 100 mK in fields up to 7 T by means of a sensitive capacitance torque magnetometer [6] mounted on the tail of a dilution refrigerator. The sample is attached to the moving spring of the torquemeter with a thin layer of N-Apiezon grease. This spring is covered with a 20 μm thick gold layer to obtain good thermal contact of the sample with the refrigerator tail. The superconducting current density $j_s(T,B)$ is measured by performing hysteresis loops around selected values of the magnetic field. This is done with 8 different sweep rates dB/dt ranging from 40 to 0.3 mT/s in order to extract the

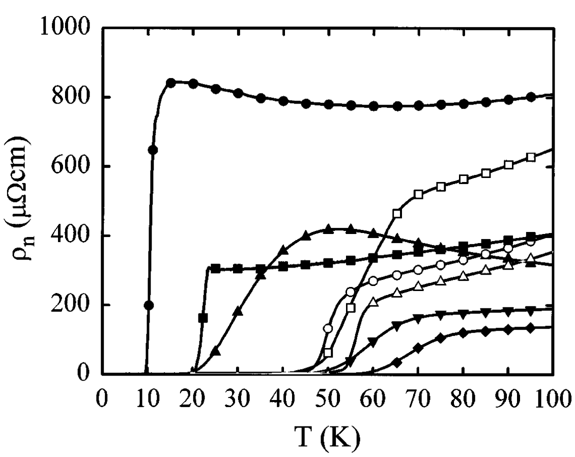

FIG. 1. Temperature dependence of the normal state resistivity ρ_n of the dirty HTS's $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ A (■), $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ B (●), $(YBa_2Cu_3O_7)_n/(PrBa_2Cu_3O_7)_8$ with $n = 1$ (▲), $n = 2$ (▼), and $n = 3$ (◆), $YBa_2Cu_3O_x$ with $x = 6.55$ (□), $x = 6.6$ (○), and $x = 6.7$ (△). The corresponding quantum relaxation rates $Q(0)$ at $B = 1$ T are given in Table I.

dynamic relaxation rate $Q(T,B) = d\ln j_s/d\ln(dB/dt)$ [7]. The results for $B = 1$ T are reported in Table I, where we also indicate the relevant parameters for the other examined dirty compounds [8].

The parameter $\omega\tau$ in Table I has been calculated at $T = 0$ K using Eq. (2) where $\rho_n(0)$ is reliably found from linear extrapolation of $\rho_n(T)$ to 0 K. We conclude that all the compounds mentioned in Table I are indeed in the dirty limit. The quantum relaxation rate $Q(0)$ is found from extrapolating the measured $Q(T)$ down to 0 K. This is done for $B = 1$ T, above which the relaxation rate is roughly field independent for all examined samples. According to Eq. (1) for $(YBa_2Cu_3O_7)_1/(PrBa_2Cu_3O_7)_8$, $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ A and B, these values would lead to $L_c(0) \cong 13$, 28, and 38 nm, respectively, which does not make sense for the single unit cell $(YBa_2Cu_3O_7)_1/(PrBa_2Cu_3O_7)_8$ and for the highly anisotropic $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ ($\gamma \approx 55$ [9]). In order to explore the origin of this discrepancy we consider dissipative quantum creep in more detail.

As calculated exactly by Larkin and Ovchinnikov [10] for the case of a cubic potential well of the form $U(x) = 3U_0(x/x_0)^2(1 - 2x/3x_0)$ the tunneling probability in the presence of dissipation is

$$P \propto \exp\left(-\frac{\pi}{2}\frac{\eta(0)x_0^2(1 - j_s/j_c)}{\hbar}\right). \qquad (3)$$

Here $\eta(0)$ is the viscosity experienced by a tunneling vortex segment and x_0 the range of the effective pinning potential $U(x)$ in the absence of current. The factor $(1 - j_s/j_c)$ is due to the reduction of this range by a factor $(1 - j_s/j_c)^{1/2}$ in the presence of an external superconducting current density j_s, where j_c is the current density at which the tunneling barrier vanishes. The electric field arising from the vortices moving with velocity v_v is given by $\vec{E} = \vec{v}_v \times \vec{B}$ and therefore $E \propto P$. For the case of dynamic relaxation in which j_s is measured as a function of the magnetic field sweep rate dB/dt [7] $E \approx (r/2)(dB/dt)$ for a sample of radius r. Thus, $dB/dt \propto P$ and from the definition $Q \equiv d\ln j_s/d\ln(dB/dt)$ of the dynamic relaxation rate follows that

$$Q_{\mathrm{dirty}}(0) \approx \frac{2}{\pi}\frac{\hbar}{\eta(0)x_0^2}\frac{j_c(0)}{j_s(0)} \approx \frac{2}{\pi}\frac{\hbar}{\eta(0)\xi_{ab}^2(0)}\,, \qquad (4)$$

since $x_0 \approx \xi_{ab}(0)$ [11] and $j_s(0) \approx j_c(0)$. Equation (4) shows explicitly that quantum creep in dirty HTS's can be used to measure the viscosity $\eta(0)$ (Table I).

All papers published so far on the dissipative tunneling of vortices use the Bardeen-Stephen expression [4]

$$\eta(0) = \frac{\phi_0 B_{c2}(0) L_c(0)}{\rho_n(0)} \qquad (5)$$

for the viscosity experienced by a cylindrical vortex segment with length $L_c(0)$ and radius $\xi_{ab}(0)$. For strongly layered compounds Blatter *et al.* [3] argue that $L_c(0)$

TABLE I. Parameters for the dirty high-T_c superconductors considered in this work. n_s is the density of superconducting electrons evaluated using $n_s \approx 3.5 m_e/\mu_0 e^2 \lambda_{ab}^2(0)$ found for the values of various high T_c superconductors in Refs. [16], [17], and [22]. The quantum creep rate $Q(0)$ is found from a linear extrapolation of $Q(T)$ measured down to 100 mK for $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ A and B and down to 1.7 K for the other compounds. $\omega\tau(0)$ is calculated by means of Eq. (2) and the viscosity $\eta(0)$ by means of Eq. (4).

	T_c (K)	$\rho_n(0)$ ($\mu\Omega$ cm)	$\lambda_{ab}(0)$ (nm)	n_s (10^{27} m^{-3})	$\xi_{ab}(0)$ (nm)	$Q(0)$ at 1 T	$\omega\tau(0)$	$0.1/n_s\xi^3\omega\tau$	$\eta(0)$ (10^{-17} kg/s)
PCeCO B	12.1	895	90[a]	12	7.3	0.055	0.0004	0.054	2.3
PCeCO A	23.2	300	85[a]	13.8	5.6	0.025	0.002	0.021	8.6
$(YBCO)_1/(PBCO)_8$	42	560	375[b]	0.7	2.4[e]	0.1[f]	0.090	0.11	11.7
$(YBCO)_2/(PBCO)_8$	67	150	235[b]	1.8	2.0[e]	0.035[f]	0.189	0.037	48.0
$(YBCO)_3/(PBCO)_8$	77	90	195[b]	2.6	1.8[e]	0.025[f]	0.268	0.025	82.9
$YBCO_{6.55}$ thin film	66	325	175[c]	2.5[d]	2.4[c]	0.055[g]	0.044	0.066	21.2
$YBCO_{6.6}$ thin film	52	155	165[c]	3.4[d]	2.2[c]	0.035[g]	0.082	0.034	39.6
$YBCO_{6.7}$ thin film	57	95	155[c]	4.6[d]	1.9[c]	0.03[g]	0.130	0.024	62.0

[a]Reference [14]. [b]Reference [15]. [c]Reference [16]. [d]Reference [17]. [e]Reference [18]. [f]Reference [19]. [g]Reference [20].

should be replaced by d, the separation between superconducting CuO_2 planes which is $\approx$1.2 nm for the highly anisotropic dirty HTS's examined here. In order to check the validity of the Bardeen-Stephen expression we looked for a correlation between the effective length

$$L_{\mathrm{eff}} \equiv \frac{\eta(0)\rho_n(0)}{\phi_0 B_{c2}(0)} \approx \frac{4}{\pi^2}\frac{e^2}{\hbar}\frac{\rho_n(0)}{Q(0)} \tag{6}$$

[from Eqs. (4) and (5)] and typical lengths such as $L_c(0), d, \xi_{ab}(0), \xi_c(0), \lambda_{ab}(0), \ldots,$ characterizing the superconducting state of the host material. The only significant correlation that could be found is shown in Fig. 2: It implies $L_{\mathrm{eff}} \approx 2.1\xi_{ab}(0)$. This is a striking result as can be seen best from the data for the HTS's $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ which have a large $\xi_{ab}(0)$ and at the same time a large anisotropy. For samples A and B we find $L_{\mathrm{eff}} \approx 2.1\xi_{ab}(0) = 9.9d$ and $12.8d$, respectively, while $L_{\mathrm{eff}} \approx L_c(0) = d$ is expected theoretically since $\gamma \approx 55$. The correlation found in Fig. 2 implies, when a vortex segment moves under the action of the Lorentz force generated by superconducting currents, that dissipation is taking place in a volume $\sim\xi_{ab}^3$, even for highly anisotropic HTS's where a much smaller volume $\sim\xi_{ab}^2 d$ is moving in case of a vortex pancake. This might be due to the fact that vortex motion generates a homogeneous electric field $\vec{E} = \vec{v}_v \times \vec{B}_{c2}$ inside the normal core but also a dipolar electric field outside the core. This induces a normal current to run not only in the CuO_2 planes to which the pancake belongs but also in the normal cores of pancakes in adjacent CuO_2 layers. The vertical extension of the region in which normal currents are flowing can be estimated by considering the current flow pattern in a resistive conductor, which is indeed of the order of ξ_{ab}.

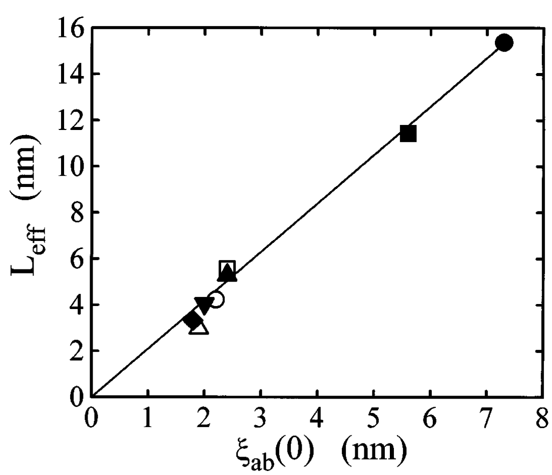

FIG. 2. The effective length L_{eff} defined in Eq. (6) versus $\xi_{ab}(0)$ at $T = 0$ K for the dirty high-T_c superconductors $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ A (■) and B (●), $(YBa_2Cu_3O_7)_n/(PrBa_2Cu_3O_7)_8$ multilayers with $n = 1$ (▲), $n = 2$ (▼), and $n = 3$ (◆), $YBa_2Cu_3O_x$ with $x = 6.55$ (□), $x = 6.6$ (○), and $x = 6.7$ (△). The line is a linear fit implying $L_{\mathrm{eff}} \approx 2.1\xi_{ab}(0)$.

Therefore we suggest that $L_c(0)$ in Eq. (5) should be replaced by L_{eff}, the length of the volume in which dissipation takes place. The latter quantity is determined in experiments since the relaxation rate $Q(0)$ depends on the dissipative volume $\sim L_{\mathrm{eff}}\xi_{ab}^2$ and not on the volume $\sim L_c\xi_{ab}^2$ of the tunneling vortex segment. We expect the assumption $L_c = L_{\mathrm{eff}}$ of the Bardeen-Stephen theory to be valid only in case of low anisotropy where the moving vortex segments have $L_c > d$, since for highly anisotropic dirty HTS's it clearly leads to an underestimation of $\eta(0)$. Equations (2), (4), and (5) then lead to $Q_{\mathrm{dirty}}(T = 0, \omega\tau) \approx 2/\pi^2 n_s 2.1\xi_{ab}^3\omega\tau \approx 0.1/n_s\xi_{ab}^3\omega\tau$, giving rise to values which are close to the observed $Q(0)$ (Table I) and which are smaller than $Q_{\mathrm{dirty}}(T = 0, \omega\tau) \approx 2/\pi^2 n_s\xi^2 d\omega\tau$ expected on the basis of the Bardeen-Stephen theory.

Having determined L_{eff} we can calculate the viscosity $\eta_l(0)$ per unit length using Eq. (4) and the definition $\eta_l(0) \equiv \eta(0)/L_{\mathrm{eff}} \approx 0.95\hbar/\pi Q(0)\xi_{ab}^3(0)$. Interestingly the values for $\eta_l(0)$ determined in this way from our quantum creep rates are comparable to the values of $\eta_l(0)$ found by high frequency surface impedance measurements. The latter techniques probe the intra-well-vortex motion and are very distinct from relaxation measurements which probe the motion between adjacent pinning

TABLE II. Parameters for the clean high-T_c superconductors considered in this work. $Q(0)$ is found from a linear extrapolation of $Q(T)$ measured down to 100 mK for all compounds except $Bi_2Sr_2CaCu_2O_8$ which was measured down to 1.7 K.

	T_c (K)	$\rho_n(0)$ ($\mu\Omega$ cm)	$\lambda_{ab}(0)$ (nm)	n_s (10^{27} m^{-3})	$\xi_{ab}(0)$ (nm)	$Q(0)$ at 1 T	$\omega\tau(0)$
$YBa_2Cu_3O_{7-\delta}$ thin film	92	<10	142[a]	5.8[b]	1.6[c]	0.017	>1.32
$YBa_2Cu_3O_{7-\delta}$ single crystal	92	<10	142[a]	5.8[b]	1.6[c]	0.017	>1.32
$YBa_2Cu_4O_8$ thin film	80	<10	198[a]	2.8[a]	2.0[d]	0.022	>1.83
$Tl_2Ba_2CaCu_2O_8$ thin film	114	<15	221[a]	2.0	2.0[e]	0.027	>1.71
$Bi_2Sr_2CaCu_2O_8$ single crystal	88	<15	250[a]	1.5	2.1[f]	0.029[g]	>2.07

[a]Reference [21]. [b]Reference [17]. [c]Reference [22]. [d]Reference [23]. [e]Reference [24]. [f]Reference [25]. [g]Reference [26].

sites. Nevertheless, for $YBa_2Cu_3O_7$ Golosovsky *et al.* [12] report $\eta_l(0) \approx 3.8 \times 10^{-7}$ kg/s m from high frequency measurements, while we find 1.6×10^{-7} kg/s m for $YBa_2Cu_3O_{6.7}$. Our lower value is understandable since $YBa_2Cu_3O_{6.7}$ is dirtier than $YBa_2Cu_3O_7$ which is in the clean limit (see below).

(ii) *Quantum creep in clean HTS's.*—Table II summarizes the measured quantum creep rates for HTS's with a relatively low extrapolated $\rho_n(0)$. For all these compounds we find $\omega\tau(0) \geq 1$, implying that they are in the clean limit.

The tunneling probability in the clean limit is given by Feigel'mann *et al.* [13] as

$$P \propto \exp(-\pi n_s V), \tag{7}$$

where n_s is the density of superconducting electrons and V the volume enclosed by the tunneling trajectory of the vortex segment. In this case the expression for the quantum relaxation rate becomes $Q_{\mathrm{clean}}(0) = 1/\pi n_s V(0)$. From Table II we conclude that at $B = 1$ T a quantum relaxation rate $Q(0)$ of the order of 0.022 is a general feature of the various investigated compounds. This implies that the amount of superconducting charge carriers within the volume enclosed by the trajectory of the vortex segment, $n_s V(0) = 1/\pi Q(0)$, is a material independent parameter of the order of 14 for clean superconductors.

In conclusion, we have shown that the quantum creep behavior of dirty and clean HTS's can be consistently rationalized. Our results call for a new treatment of dissipation of moving vortices. In a forthcoming paper we shall propose an interpolation formula to describe quantum creep for any value of $\omega\tau$, i.e., from the dirty to the clean limit.

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[8] $\xi_{ab}(0)$ is evaluated using the Werthamer formula $B_{c2}(0) \approx -0.7\, dB_{c2}/dT|_{Tc} T_c$ with the Ginzburg-Landau relation $B_{c2}(0) = \phi_0/2\pi\xi_{ab}^2(0)$ for the samples with $B_{c2}(0)$ far outside the experimental range. It is determined resistively and via torque measurements for the $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ samples.
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